Prepared for submission to JINST

Topical Workshop on Electronics for Particle Physics
September 19-23, 2022
Bergen, Norway

Radiation tolerance studies of the HV-mux GaNFETs for the HL-LHC ATLAS ITk Strip Detector

F. Capocasa,[a] W. Fielitz,[b] L.F. Gutierrez Zagazeta,[c,1] J. Kierstead,[b] D. Lynn,[b] C. Musso[b] S. Stucci[b]

[a] *Martin A. Fisher School of Physics, Brandeis University, Waltham, Massachusetts, USA*
[b] *Department of Physics, Brookhaven National Laboratory, Upton, New York, USA*
[c] *Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, Pennsylvania, USA*

E-mail: luis.felipe.gutierrez.zagazeta@cern.ch

Abstract: For the High-Luminosity upgrade of the LHC, the current ATLAS inner detector will be replaced with a new silicon charged-particle tracker, the ITk, which consists of the ITk Pixel and ITk Strip subdetector. The high voltage multiplexing (HV-Mux) GaNFETs are radiation-tolerant transistors that permit switching off high voltage to malfunctioning sensors on the ITk Strip modules. To ensure the reliability of the GaNFETs in the high radiation environment expected at the HL-LHC, a sample of the production batch was exposed to gamma radiation. The GaNFETs were characterized pre-irradiation and post-irradiation, and monitored during irradiation.

Keywords: GaNFETs; Radiation-hard detectors; Radiation-hard electronics; Radiation-hard transistors

ATL-ITK-PROC-2022-029
19 October 2022

[1] Corresponding author

Contents

1 ATLAS Inner Tracker upgrade for the HL-LHC

The High-Luminosity phase upgrade of the Large Hadron Collider (HL-LHC) is expected to reach a peak instantaneous luminosity of $7.5 \times 10^{-34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, delivering more than $3000\,\mathrm{fb}^{-1}$ proton-proton collisions. The result is a busy charged-particle tracking system along with a harsher radiation environment for all the detector components [2] [3].

To guarantee the success of the ATLAS experiment [1], the current ATLAS inner detector (ID) will be replaced with the Inner Tracker (ITk), an all-silicon based tracking system. The ITk detector will have higher granularity, faster readout, and significantly more radiation tolerance than the current ATLAS ID. The ITk consists of two subsystems: ITk Pixel detector [2] and ITk Strip detector [3].

2 GaNFETs for the ATLAS ITk Strip detector

The ITk Strip subdetector is composed of carbon composite structures loaded with modules, which house two types of ASICs responsible for data readout: ATLAS Binary Chip (ABCStar) and Hybrid Control Chip (HCCStar) [3]. In addition, each module's power-board contains an Autonomous Monitoring and Control Chip (AMACStar) responsible for control of the module and monitoring of voltages, currents and temperatures, and a GaNFET responsible for switching off the sensor's high biased voltage [3].

As there is not sufficient space to provide a bias voltage to each module, up to 4 modules share a single high voltage (HV) bias line. If one module's sensor goes into breakdown, all the modules sharing the same HV bias become nonfunctional. To avoid losing multiple modules from a single failure, GaNFETs, commercial Panasonic radiation-tolerant gallium nitride transistors, are installed in each module's power board to be operated as HV switches. The GaNFETs drain-source voltage is the module's HV and the GaNFET state is controlled by the AMACStar through the gate drive circuity by providing either 0 or 3.3 V to the gate [4].

The radiation tolerance design of these GaNFETs needs to be tested to ensure their operability throughout the tracker's lifetime. A sample of the production batch of GaNFETs was exposed to $\sim$1 MeV gamma radiation at Brookhaven National Laboratory (BNL) to study the effects of total ionizing dose (TID) on the transistors like changes in properties such as voltage threshold shifts.

3 Characterization

Three tests were developed to characterize the performance of GaNFETs: voltage threshold, current leakage in the off-state and operability under detector-like conditions.

AMACStar controls the GaNFET gate voltage through an oscillating 3.3 V to the HV-mux [4]. The GaNFETs voltage threshold always needs to be significantly below 3.3 V to avoid losing control of the sensor bias HV. The voltage threshold of each GaNFET in the testing sample was gathered by providing a large current (2 A) for a short period of time (100 μs).

The current leakage of the GaNFET in the off-state is measured to ensure the HV to the neighboring modules is insignificantly affected when a sensor fails. This is achieved by using a dual-channel picoammeter to simultaneously measure the current through the gate and source of the GaNFET as a function of drain-source voltage.

Furthermore, there are strict requirements on the maximum current consumed by each GaNFET. The current consumption in the off-state and on-state with realistic detector conditions were measured. A 265.4 kΩ resistor and 1 GΩ resistor were used to imitate the impedance of an irradiated detector and a new detector, respectively.

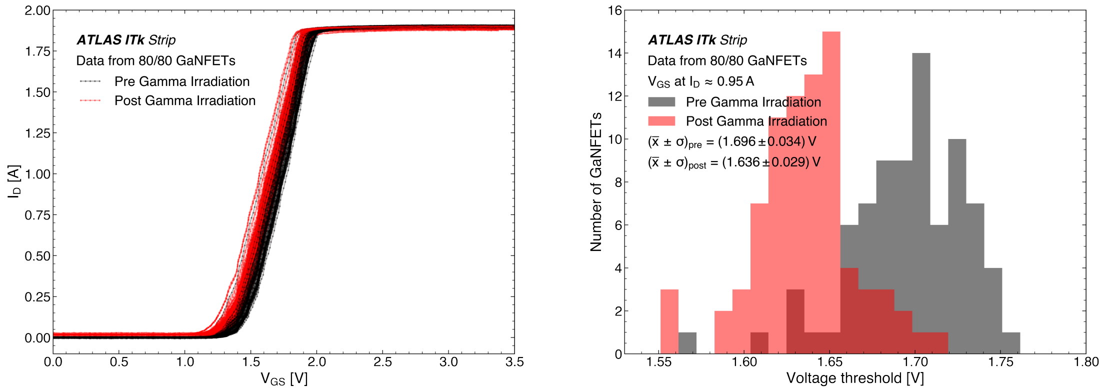
4 Gamma irradiation

A total of 80 GaNFETs were irradiated with gamma radiation at room temperature. Due to slight setup misalignment, the GaNFETs received a variable dose rate between 27.6 and 29.4 krad/hr. For simplicity, the TID was determined using the lowest dose rate to ensure every GaNFET experiences a TID of at least 50 Mrad.

In the ITk Strip detector, GaNFETs will only operate in the off-state if a module's sensor fails. Therefore, 60 GaNFETs were irradiated in the on-state and 20 GaNFETs were irradiated in the off-state. Throughout the irradiation, the state of each GaNFET was monitored to precisely determine failure points. Additionally, the state of each GaNFET was switched every 3 hours to verify the device was still properly operating. The monitoring of the GaNFETs was minimally interrupted due to communication issues, but irradiation continued. Also, the HV power supply tripped twice. The first cause was a power short on the HV connector due to the deterioration of the internal insulating material. This did not affect the GaNFETs since each testing location contained protecting diodes. The second case happened at a TID of 49.5 Mrad due to excessive current caused by the failure of at least one GaNFET. To avoid testing interruptions, the GaNFETs continued getting irradiated without HV for the last 0.5 Mrad.

4.1 Results

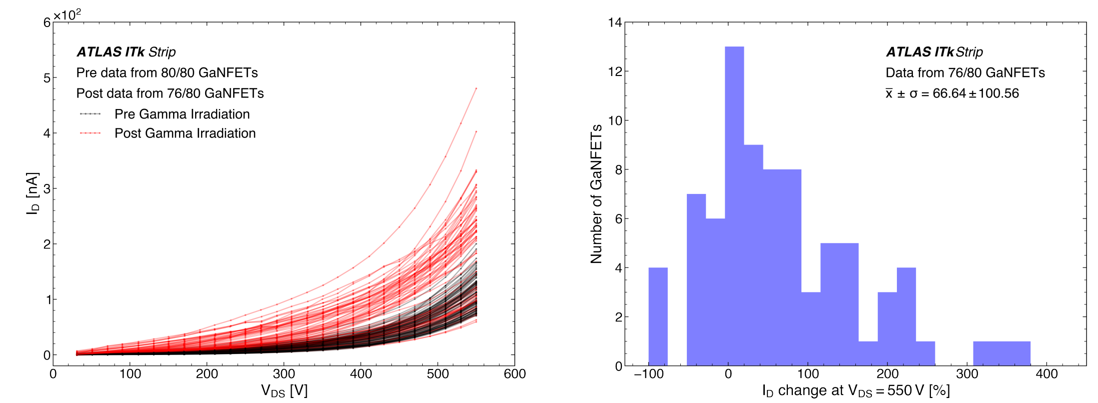
Figure 1b shows an average shift of $(-3.5 \pm 0.1)\%$ in the GaNFETs voltage threshold. The voltage threshold shift is minimal and will have no effects on detector operations.



(a) (b)

Figure 1: Data collected with 10 V supplied to the drain through a 5.1 Ω current limiting resistor. (a) GaNFET drain current as a function of gate-source voltage. (b) GaNFET voltage threshold before and after being exposed to gamma radiation for a TID of 50 Mrad. The voltage threshold is taken at a drain current ∼0.95 A.

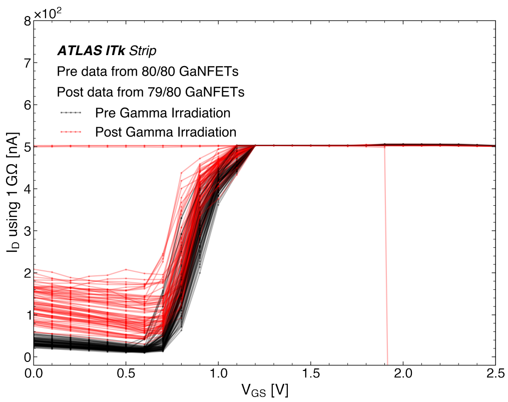
Moreover, an increase in off-state current leakage is shown in Figure 2. Considering only the GaNFETs that were still operational after the gamma irradiation, the current leakage at a drain-source voltage of 550 V increased by (66.6 ± 100.6) % with a maximum drain leakage current of about 490 nA. The increase will have no effect on the operations of the detector since each sensor's is expected to require ∼100 μA or more. Also, four off-state GaNFETs failed the post-irradiation current leakage test due to excessive HV current consumption.



(a) (b)

Figure 2: Data collected with the gate-source voltage grounded. Four GaNFETs irradiated in the off-state failed due to excessive drain current post-irradiation (a) GaNFET drain current as a function of drain-source voltage. (b) Change in off-state current relative to the pre-irradiation data at a drain-source voltage of 550 V.

Furthermore, the detector-like conditions test shows that 76 out of 80 GaNFETs can still be controlled under detector-like conditions. Figure 3 shows that 3 out of 80 irradiated GaNFETs are effectively always in the on-state, and data from 1 GaNFET could not be obtained post-irradiation due to an over-the-limit HV current during testing. Figure 3a shows that the off-state drain current increased after the irradiation. However, Figure 3b shows that the increase in off-state drain current is minimal at the expected end of lifetime condition.



(a) (b)

Figure 3: Detector-like conditions test results. Data collected using a 1 GΩ and 265.4 kΩ current limiting resistor to simulate the expected currents of a new and an irradiated detector, respectively. Four GaNFETs are effectively always in the on-state. Post-irradiation data from one GaNFET is not available due to over-the-limit current. The GaNFET drain current as a function of gate-source voltage is shown assuming (a) a new detector, and (b) an irradiated detector.

The four failing GaNFETs, with identification number 9, 20, 60 and 70, were irradiated in the off-state and they failed after a TID of 36.0 Mrad, 32.8 Mrad, 30.7 Mrad and 45.5 Mrad, respectively. The monitoring results of one of the failing GaNFET is shown in Figure 4. Although the off-state GaNFET failure rate is 20%, GaNFETs are expected to operate in the off-state only after the module's sensor fails. Two of the failing GaNFETs had a single event burnout (SEB) during irradiation, one of which can be seen in Figure 5.

5 Conclusions and outlook

60 out of 60 GaNFETs radiated in the on-state remained operational up to a minimum TID of 50 Mrad. 4 out of 20 GaNFETs radiated in the off-state failed at a minimum TID of 30.7 Mrad. 2 of the failing GaNFETs experienced a SEB. The 4 failing GaNFETs had large current consumption in the off-state effectively always being in the on-state for ITk Strip detector purposes. GaNFETs will be in the off-state only when modules fail, so the use of the GaNFET can only increase the lifetime of the modules sharing the HV bias line even if it later fails.

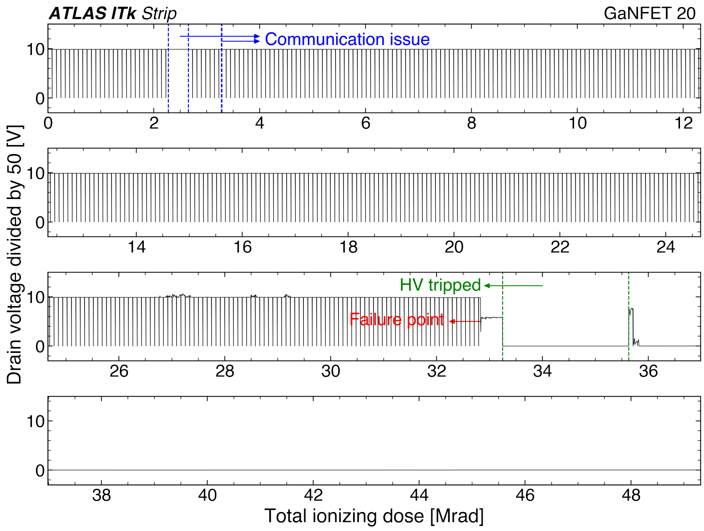


Figure 4: GaNFET 20 monitoring during irradiation. The monitored value is the drain voltage after passing through a 1/50 voltage divider as a function of TID. Failure observed at a TID of 32.8 Mrad were drain voltage oscillations reflect unexpected drain current leakage.

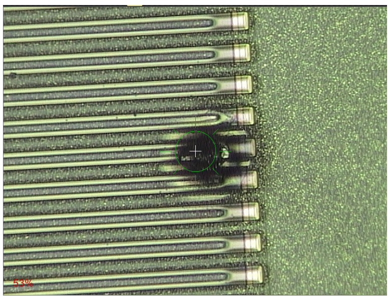


Figure 5: GaNFET 20 post-irradiation SEB.

Acknowledgments

The authors would like to honor and thank Phillip Kuczewski, who, although no longer with us, developed the hardware and software needed for the testing of the GaNFETs at BNL. Without his contribution, none of this would have been possible.

References

[1] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, JINST 3 S08003, 2008

[2] ATLAS Collaboration, *Technical Design Report for the ATLAS Inner Tracker Pixel Detector*, Tech. Rep. CERN-LHCC-2017-021, 2017

[3] ATLAS Collaboration, *Technical Design Report for the ATLAS Inner Tracker Strip Detector*, Tech. Rep. CERN-LHCC-2017-005, 2017

[4] E.G. Villani et al., *HVMUX, the High Voltage Multiplexing for the ATLAS Tracker Upgrade*,JINST 12 C01076, 2017

[5] T. Harsuda et al., *Reliability of Hybrid-Drain-embedded Gate Injection Transistor*, DOI:10.1109/IRPS.2017.7936308, IEEE International Reliability Physics Symposium, 2017